Sensor Fusion in the Early Wear Regime for Condition –Based Maintenance

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Abstract
Initial results from an Office of Naval Research-funded programme being conducted by the University of Wales Swansea and the Naval Research Laboratory (NRL) at Washington DC are reported. Several laboratory-based test machines are utilised to generate specific types of wear behaviour, notably in the early wear regime of failing component contacts. The principal condition monitoring techniques currently being deployed comprise, respectively, acoustic emission, vibration and wear debris analysis. The purpose of the experimental test programmes being conducted at Swansea is primarily that of establishing how each technique responds, singly and in combination, to the early indications of surface distress. Collaboration between Swansea and NRL is aimed at developing appropriate means for processing sensor data in relation to the detection and diagnosis of active wear. The expectation is that, ultimately, the remaining useful life of critical components can be reliably predicted, thereby contributing to future improvements in the way critical operating equipment is protected and maintained.

1. Introduction
Condition-based maintenance has been an integral part of maintenance strategy and activity in many industrial and government controlled establishments for more than two decades. Traditional methods, such as visual inspection, performance monitoring and lubricant analysis, continue to play an important part in the monitoring activity. More recently, considerable emphasis and effort has been given to developing powerful, computer-based techniques, notably, in relation to vibration (and noise) analysis, and also in wear debris analysis. However, there has not been so far sufficient emphasis given to systematically developing a co-ordinated strategy for integrating these two major monitoring technologies, especially in the early wear regime of machine deterioration. The essential elements of any machinery health monitoring programme comprises, ideally:

***Detection* of the problem**
***Diagnosis* of the type and source of the problem**
***Decisions* regarding what needs to be done, and when.**

In the context of present global military functions it is becoming increasingly evident that information should, ideally, be made available without recourse to requiring intensive human expert procedures for obtaining and interpreting the monitored data. To achieve such a laudable aim requires the combined knowledge, expertise and resources of a number of active and co-operative participants. In the context of the programme described in this paper, the combined experience and resources of two research and development groups are being brought to bear to focus on the problem. In the UK, the University of Wales, Department of Mechanical Engineering, and in the USA, the Naval Research Laboratory, (NRL) Washington, DC. The programme thereby seeks to build on the recent development of a sensor-based wear debris analysis technique - the LASERNET FINES system at NRL, by coupling it to developments in wear debris analysis at Swansea combined with acoustic emission and vibration monitoring allied to feature vector analysis, (1-5).

In order to further develop the technology it is eminently sensible, on the one hand, to collect debris and sensor (vibration et al) data under controlled laboratory conditions, in which distress-related functions, such as friction, lubrication and wear conditions, are suitably controlled and/or determined. On the other hand, such activity must be commensurate with ensuring that the data obtained yields information that is directly relevant to those responsible for carrying out the maintenance function in the field.

In this paper, the methods adopted in performing laboratory-based wear tests will be described in conjunction with the techniques devised to monitor the wear state in terms of, respectively, wear debris, acoustic emission and vibration analysis.

2. Integration of condition monitoring systems

In recent years there has been a proliferation of techniques and methodologies introduced for monitoring critical industrial machinery (6-9). Broadly, four distinct families of monitoring systems are commonly utilised in industry:

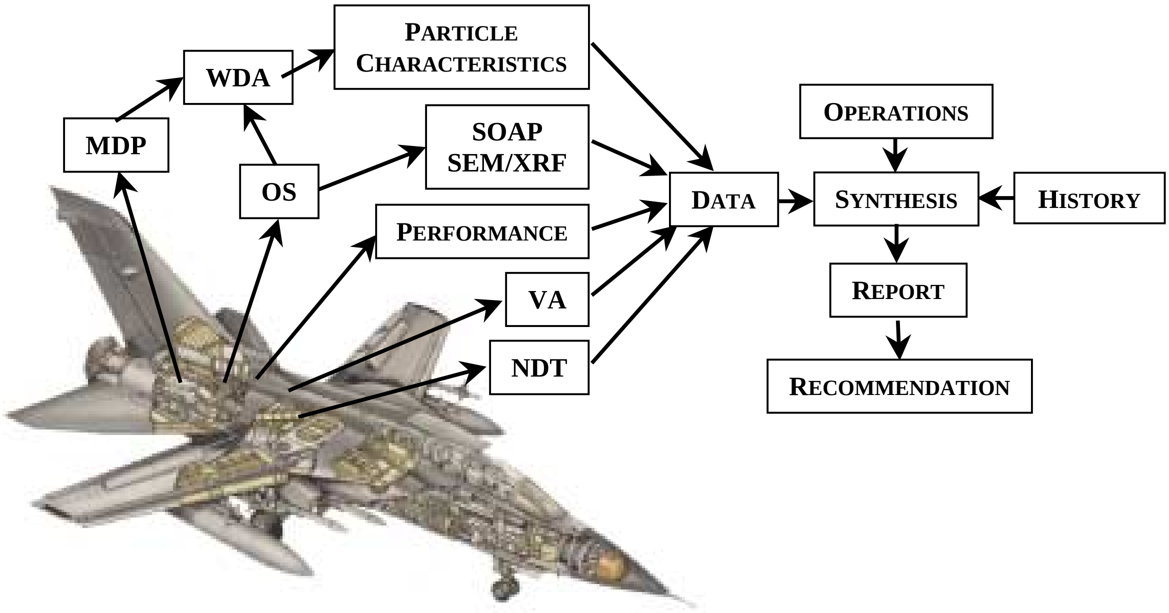
- Visual inspection, notably endoscopy (and, human senses generally – noise, smell, etc.)
- Performance monitoring (temperature, pressure, flow-rate, motor current, etc.)
- Noise and Vibration analysis
- Oil and Wear Debris analysis

There is, in addition, the important area of non-destructive testing which also provides invaluable information about the deterioration of equipment that would otherwise lie hidden to naked eye or ear. Of the four above-mentioned categories, the latter two have received considerable attention in developing ways to ‘listen-in’ on what is happening as a function of time or operating condition. Figure 1 shows, illustratively, the range of monitoring devices deployed in relation to the present-day maintenance of military aircraft in the European sector, in which a primarily ‘off-line’ monitoring strategy is used. The stated intention for future monitoring and maintenance of US military aircraft is that it should be a largely on-line, remote sensing system, (10)**.**

The projected costs for the loss of just one aircraft are enormous. Total cost avoidance in 1992 for just five removals of engines from F-16 jet aircraft before incurring serious engine damage was $15,000,000, (11). Clearly, monitoring techniques that can be utilised either singly, or in combination, already constitute well- developed and utilised practices in many companies. However, how they perform in relation to early signs of wear-related distress is presently not yet properly understood, or researched. Hence, the main thrust and impetus of this investigation is to systematically study and establish the following:

- How each technique performs singly under verifiable wear conditions
- How they relate to one another in tracking surface distress deterioration of rubbing components
- How they can best be utilised in a remote sensor environment to provide data in order to determine the remaining useful life of critical components

To perform such an investigation requires that there are suitable test devices that can replicate in the laboratory various forms of wear behaviour that are known to occur in practice, and that appropriate means exist for monitoring the situation using more than one technique simultaneously.



Key

MDP = Magnetic Debris Plug
WDA = Wear Debris Analysis
OS = Oil Sample
VA = Vibration Analysis
SOAP = Spectrometric Oil Analysis Program
SEM = Scanning Electron Microscope
XRF = X-Ray Florescence
NDT = Non-Destructive Testing

Figure 1 Monitoring systems utilised for condition-based maintenance of aircraft

3. Wear behaviour – a brief overview

Wear is a complex, multi-disciplinary process requiring, ideally, chemical and physical knowledge of lubricant and surface properties coupled to geometry and motion which is usually related to micro-size areas of highly stressed rubbing contacts. However, it is generally recognised that the principal categories of wear phenomena are specified in terms of: abrasion, adhesion, pitting fatigue and fretting, (12). The effects due to corrosion and erosion action are also important factors in many instances.

One of the principal consequences of wear is the generation of wear debris. Knowledge of the processes involved has been known for many years, but detailed analysis of their features as a means to determine wear and failure of operating machinery is a comparatively recent activity. This was prompted in the first instance by the need to establish improved methods for analysing the lubricating oil in order to give early warning of impending failure of jet aircraft engines, (13). The method devised, known as ferrography, is based on the principle of separating the debris from a lubricant sample by magnetic attraction. The method is quite distinct from the alternative method of using magnetic devices located in the lubricating system which capture magnetically susceptible debris in-situ,(14). The latter method is employed extensively as part of the condition-based maintenance operations in the European sector, (10). It is not so widely used in conjunction with US military aircraft maintenance servicing requirements. The main categories of wear debris, captured and analysed using the ferrography method, are designated as follows: ferrous free metal, other metallics, oxides, and non-metallics (polymerics). The morphological features of ferrous free particles are broadly designated as: rubbing, (mild abrasion) cutting, (severe abrasion), severe sliding, (adhesion) and fatigue (pitting).

The way in which wear debris is analysed and categorised in relation to the underlying wear process are represented schematically in Figure 2. The quantity (concentration of debris), together with the size characteristics, enable the severity and rate of wear to be monitored. They are both determined by quantitative methods and thereby provide the means for establishing objectively the manner in which a machine is deteriorating as a function of time. The size distribution of the sample population coupled to morphological analysis serves to provide the best indication of the type of wear, although the latter is essentially a qualitative procedure and is, therefore a subjective and time-consuming activity. The composition (elemental analysis) is often required to pin-point which component is wearing. This has, hitherto, been expensive in terms of both time and money; however, recently reported developments in connection with the maintenance of one type of jet aircraft in the UK indicate that this may no longer be a limiting factor when monitoring critical engine functions, (15).

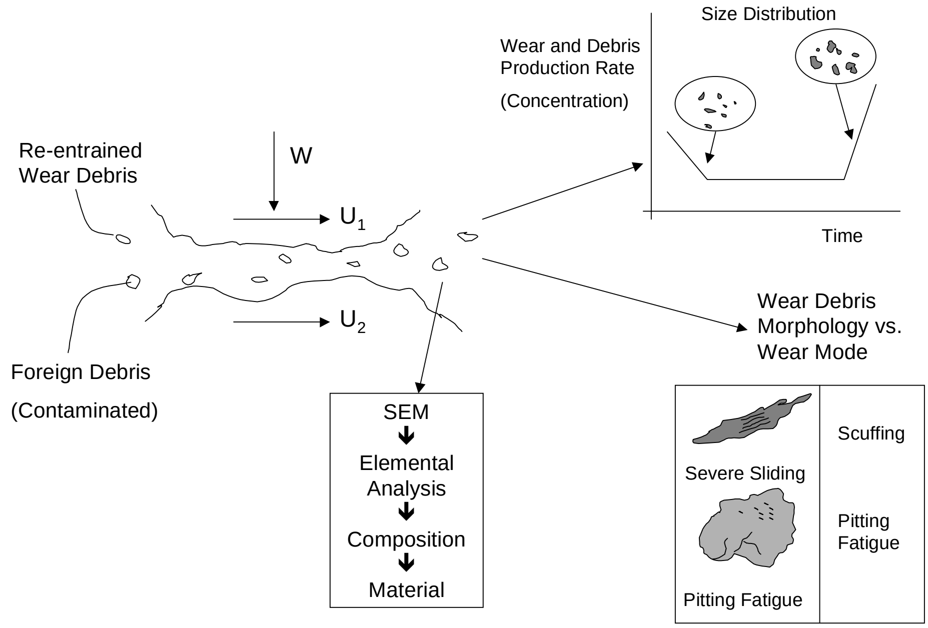


Figure 2 Wear and Wear Debris Characteristics

Regimes of lubrication

Two well-known regimes of lubrication exist at opposite ends of the performance spectrum: hydrodynamic (fluid film) and boundary lubrication. The regimes are depicted in relation to friction, load, speed and lubricant viscosity by the well-known Stribeck curve (Figure 3). Hydrodynamic lubrication provides a very high resistance to wear and is governed in part by the physical properties of the lubricant, notably viscosity. The associated frictional behaviour arises directly from viscous shearing of the lubricant. Boundary lubrication is governed by the physical and chemical properties of the interfacing surfaces and also the very thin surface films. Operating between these two extreme regimes are elasto-hydrodynamic and mixed lubrication. Elasto-hydrodynamic action occurs in highly stressed point or line contacts between machine contacting surfaces. It is a condition in which the elastic deformation of the bounding solids and the viscosity of the lubricant when subjected to high pressures (typically of the order of Giga Pascals) play a significant role in the hydrodynamic lubrication process.

Surface roughness characteristiics begin to influence the behaviour of the contact when the separation of the components approaches molecular proportions. This defines the onset of 'boundary lubrication' and is described as mixed lubrication. The nature of the contact conditions that facilitates wear in many instances might therefore best be described as a mixture of elasto-hydrodynamic and boundary lubrication.

An approximation of the regime of lubrication can thus be defined for a particular laboratory test when the operating conditions are known, together with information about the friction behaviour and the properties of the materials. Differences in the wear debris morphology are therefore of significant interest.

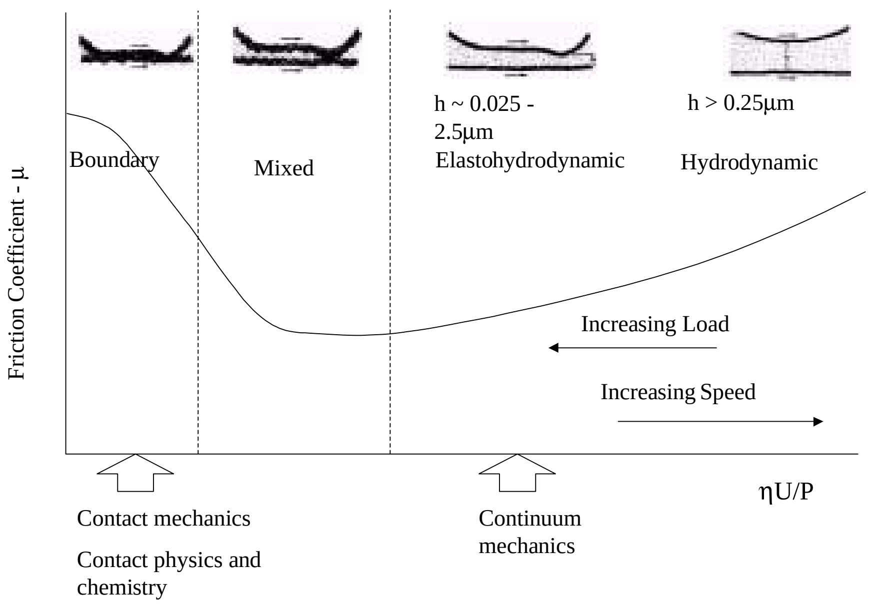


Figure 3 Relationship between friction, load, speed and viscosity – Where η = dynamic viscosity, U = speed and P = load.

Types of contact and associated wear

Sliding contact

Wear which occurs as a consequence of sliding motion is defined principally in terms of mild or severe abrasion, which may be termed as 'two- body' or 'three-body', and the more severe form which manifests itself ultimately as scuffing wear. In relation to the behaviour of lubricated systems, the prevailing regime of lubrication is a major factor in deciding what form of wear occurs. Lubricant 'cleanliness', or level of contamination, is the second most significant consideration in determining the wear mode. A clean lubricant, functioning under full film conditions in the contact, will not result in any form of wear except occasional mild wear, in which the contacting surfaces may experience periods of self- healing. The mixed regime is the region in which transitions occur from mild to severe abrasion. If the thin coherent film breaks down, or collapses, then scuffing will tend to occur as a consequence of adhesive (metal transfer) activity.

Rolling contact

Failure of operating equipment due to fatigue is arguably the most frequently encountered failure phenomenon in industrial practice. As in the case of sliding conditions, the regime of lubrication, coupled to the cleanliness level of the lubricant, are two of the most significant factors which govern the fatigue life of critical components such as rolling element bearings and gears. The development of elastohydrodynamic lubrication theory in the immediate post-war years lead the way to establishing enhanced rolling element bearing fatigue lives. This work was spearheaded by the collaboration between the aerospace industry, the bearing manufacturer and the universities, which was brought about largely as a result of the extreme demands of the 'space race' in the 1960's. Accompanying parallel developments in the use of enhanced material properties and manufacturing technology has ensured that bearing lives to-day are between one and two orders of magnitude longer than they were 50 years ago. Nevertheless, components continue to fail by this mode all too frequently. It is important therefore to obtain information about the kind of wear debris that ensues as a consequence of fatigue activity; and thence, to determine in what way their appearance differs from sliding dominated debris.

4. Test Machines and Conditions of Testing

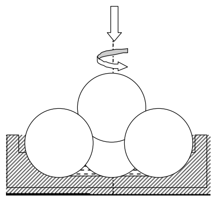
For the purpose of undertaking wear tests, four machines are utilised: Four ball, pin-on-disc, gear test and rolling element configurations. The four ball and gear test machine have been used extensively for screen testing of lubricants and are designated standard Institute of Petroleum tests; IP 239/67 and 300/75 for the four ball sliding and rolling contact conditions, respectively. The gear machine standard test is designated as IP 166/77. Figure 4 summarises the range of options available for performing a wide range of tests using the machines in terms of the control variables and the corresponding response determinations during and after the test.
Outline descriptions of each machine are as follows:

Four-ball machine

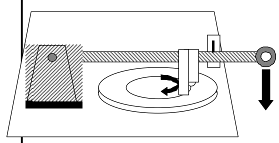
The four-ball machine, although designated as a lubricant tester, is also suitable for obtaining various types of wear debris. When used in simple sliding mode, severe sliding wear and rubbing wear particles are produced. The tests are normally quick to perform; typically, one minute of running time, and generate a substantial amount of

debris (0.5 – 4 mg) per run. In the rolling contact mode ball bearing pitting fatigue wear occurs. The test balls used are manufactured from 52100 steel. The machine utilises a variable speed DC motor that permits the spindle speed to be varied from 500 rpm to 3000 rpm. The loading is dependent on the type of test being carried out. In the case of the severe sliding, the load applied ranges typically from 35 kg to 150 kg or higher. For pitting fatigue tests, the load range is 500kg to 800 kg.
The debris is collected at the end of each test by systematically cleaning each component with solvent and discharging the test lubricant and solvent containing the debris into a plastic collection bottle. Wear debris particle collection is an important part of the procedure and although it is not possible to gather every single particle it is essential that a representative sample is obtained. Tests undertaken to determine collection efficiency have shown that typically, 60-70% of the debris is transferred from the cup to the collection bottle.

4-BALL



PIN-ON-DISC

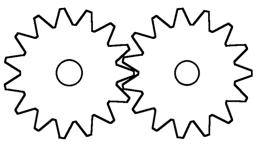


Control Variables

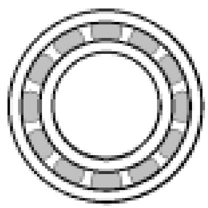
Pre-Test:	Materials Hardness	Lubricants	Roughness
On-Test:	Geometry Speed Time	Motion Temperature	Load Flow-rate

Measurement / Analysis

On-Test:	Friction Lubrication Regime and Acoustic Emission Characteristics	Temperature Vibration
Post-Test:	Surface Condition and Debris Characteristics	Wear Mode



I.A.E. GEAR RIG



NSK BEARING RIG

Figure 4 Test configurations and range of operating conditions

IAE Gear Machine

The IAE gear machine is specifically designed for investigating the anti-scuffing properties of engine oils used in aero-engine reduction gears. The gearbox test head is located at one end of the machine; there are two overhung shafts onto which are mounted a pair of test gears. Each gear is located by a spigot and is secured by set screws. The gearbox test head has a small oil jet that feeds the gears. There is a removable top cover so that the surfaces of the gear teeth can be visually inspected during a test run. The power return gearbox is located at the other end of the machine. This contains a pair of wide-faced double helical gears, and has the same teeth ratio as those in the test head, (15:16).
The gear shafts are connected together by torsion shaft, coupled together by splined sleeves. The load is applied to the gear teeth by means of a flanged load coupling. One of the gear shafts is extended at its outer end and is driven by a 10 H.P (7.5kw)

motor, through a triple v-belt pulley system. Wear debris is collected from the magnetic filter located on the return side, between the test head and the oil tank.
Table 2 summarises the test conditions and loads implemented in the current series of tests.

Table 2 Loading conditions for IAE Gear machine

Nominal conditions	*A*	*B*	*C*
Pinion speed, rpm	2000	4000	6000
Test oil temperature, C	60	70	110
Test oil flow, ml/min	285	568	568
Initial load (457.2 mm lever arm), kg	4.536	4.536	4.536
Load increment, kg	2.268	2.268	2.268
Running period, min	5	5	5
Rest period (time between running periods), min	5	5	5
Maximum load, kg	90.7	68.0	45.4
Maximum tooth face pitch loading, N/m	21000	15750	10500

Pin-On-Disc Test Machine

The pin-on-disc machine is a widely-used experimental test device for fundamental friction and wear studies, and for the development of new materials and surfaces. Essentially the test section comprises a loaded arm that moves as a result of the tangential friction force; it is pivoted at one end and is allowed to move in two planes.
The friction force between the pin and the disc is measured by a strain gauge attached to the loading arm by a hook. Its displacement is converted into a micro-strain. A specially constructed electro-magnet device, clamped behind the pin is used to collect the debris from each of the tests.

Test Machine Summary

Table 3 below summarises the details of the range of the loads and speeds produced by the four-ball, pin-on-disc and gear machines, respectively. Tables 4 and 5 provide details of the materials and lubricants used in the tests. Other machines used as part of the current investigation comprise a rolling element bearing fatigue test and a fault detection rig that permits in-balance and misalignment effects to be evaluated.

Table 3 Summary of operating conditions and materials tested for laboratory test machines

TEST CONDITIONS	TEST MACHINES		
	Four ball machine	Pin-on-disc machine	IAE Gear test Machine
Motion Sliding Rolling Sliding –rolling	 * * 	 * 	 *
Geometry Point Line Conformal	 * 	 * * *	 *
Nominal pressure (MN/m^2)	150 - 600	700-2100	350-1400
Sliding velocity (m/s)	0.25 - 1	0.1 - 10	2 - 12
Materials tested: 52100 4615 1040 *Note: See Table 5 for material surface properties*	 * 	 * * *	 *
Lubricants tested: see table 4 A B C	 * * *	 * * 	 * *

Table 4 Lubricant properties

Lubricant Properties	Lubricants		
	A	B	C
Base	Mineral	Synthetic	Synthetic
Viscosity CSt at 100 Deg C CSt at 40 Deg C	 5 30	 5 25.3	 5-5.5 25.0 min
Flash Point Deg C	226	268	246
Pour Point Deg C	-15	-54	-54

Table 5 Material properties

Material	Hardness (VHN)	Roughness Ra
52100	850	23μm
4615	779	325nm
1040	278	503nm

NSK-RHP Bearing Fatigue Test

The bearing test rig, designed and manufactured by NSK-RHP is used for testing angular contact rolling element bearings. The rig consists of four test heads with a pair of bearings mounted in each test head and loaded axially via a lever arm, providing approximately 1000kg force. Each bearing spindle is driven at 1400rpm by a 1.5kW, 3-phase, electric motor. Oil bath lubrication is employed: the lubricant is drawn from a reservoir and pumped through a filter before being gravity fed to the test bearings. Oil drained from the test heads is individually filtered, to enable debris collection, before returning to the reservoir.

Fault Detection Rig

A solid silver-steel rotor, 12mm diameter and length 750mm, is supported in two rigid bearing mounts and driven through a flexible coupling by a variable speed, 0.55kW, D.C. motor, with a maximum speed of 3000rpm. Balance discs located along the shaft can be used to adjust the extent of unbalance in the system by the addition of weights. The aluminium bearing housing can be set for varying degrees of bearing misalignment and moved to different locations along the shaft if required. The rig is not suitable for wear debris collection but can be used to investigate the behaviour of the system through vibration and acoustic emission monitoring techniques.

5. Monitoring Techniques

Figure 5illustrates schematically how each machine is utilised to obtain performance and wear data.

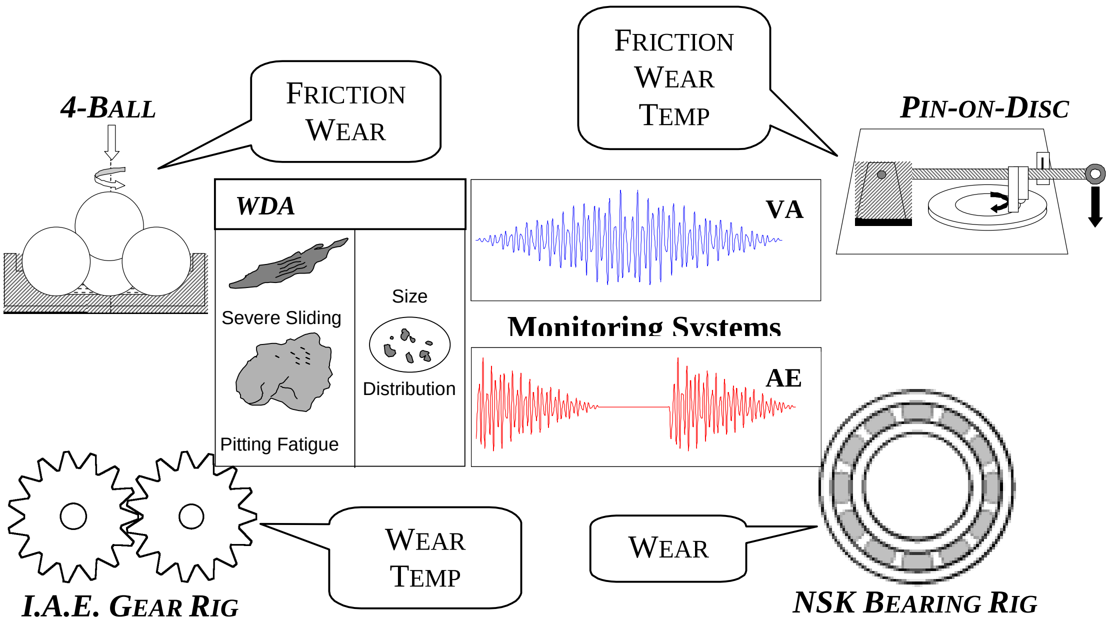


Figure 5 Performance and monitoring characteristics

Wear Debris Processing and Analysis

Details of the procedures used are reported elsewhere, (16). The debris is separated from the lubricant sample using either simple filtration or by magnetic separation, collected on a substrate and viewed using an optical microscope. Electronic images are captured from the microscope using a digital camera linked to a personal computer equipped with customised frame grabbing and image enhancing software.

The images are preserved in a customised database, together with all the relevant operating conditions and measurements. Analysis of quantity, size, shape, surface and features is undertaken using previously developed software (17). Particle composition is determined using scanning electron microscope linked to energy dispersive X-ray analysis techniques.

Vibration Analysis

Shear mode, piezoelectric accelerometers, with a resonant frequency of approximately 100kHz, are connected to a PC-based data acquisition (DAQ) system via a pre-amp and anti-aliasing filters. Analogue to digital conversion is accomplished using a 250kHz DAQ board utilising the internal PCI bus. Data collection is controlled by a custom software package and data stored to disk in Windows ASCII format.

The system is capable of monitoring vibration frequencies up to 50kHz. This is in line with current practice, in which machine noise is less prevalent in the frequency band extending from 25kHz upwards. Vibration monitoring provides information on macroscopic behaviour within machinery. (Monitoring above 50kHz is not practical given present sensor technologies.)

Acoustic Emission (AE)

AE monitoring provides the only practical method of examining frequency content above 50kHz. Piezoelectric sensors are connected to a PC-based data acquisition system via individual pre-amps. A software controlled, high speed DAQ board with onboard feature extraction and waveform buffer is used to collect transducer signals. Data is transferred to hard disk via the PCI bus. The system is capable of accepting parametric inputs and external triggers. These facilities allow synchronisation between vibration and acoustic emission data collection and logging of data representative of temperature, friction, etc.

As AE hits are generated within machinery, the sensors detect the high frequency bursts. The pre-amps filter and amplify the signals before they reach the DAQ board. Each channel has its own 10MS/s, 16-bit ADC to ensure high resolution and the capability for on-board feature extraction from waveforms. The board and associated filters are software programmable. AE hit and waveform data can be saved.

Waveforms of frequencies up to 2MHz can be digitised. This encompasses the entire spectrum of AE. The region of interest relative to this programme is up to 400kHz. AE systems are sensitive to microscopic changes within materials, thus providing a way of monitoring source events which may lead to failure.

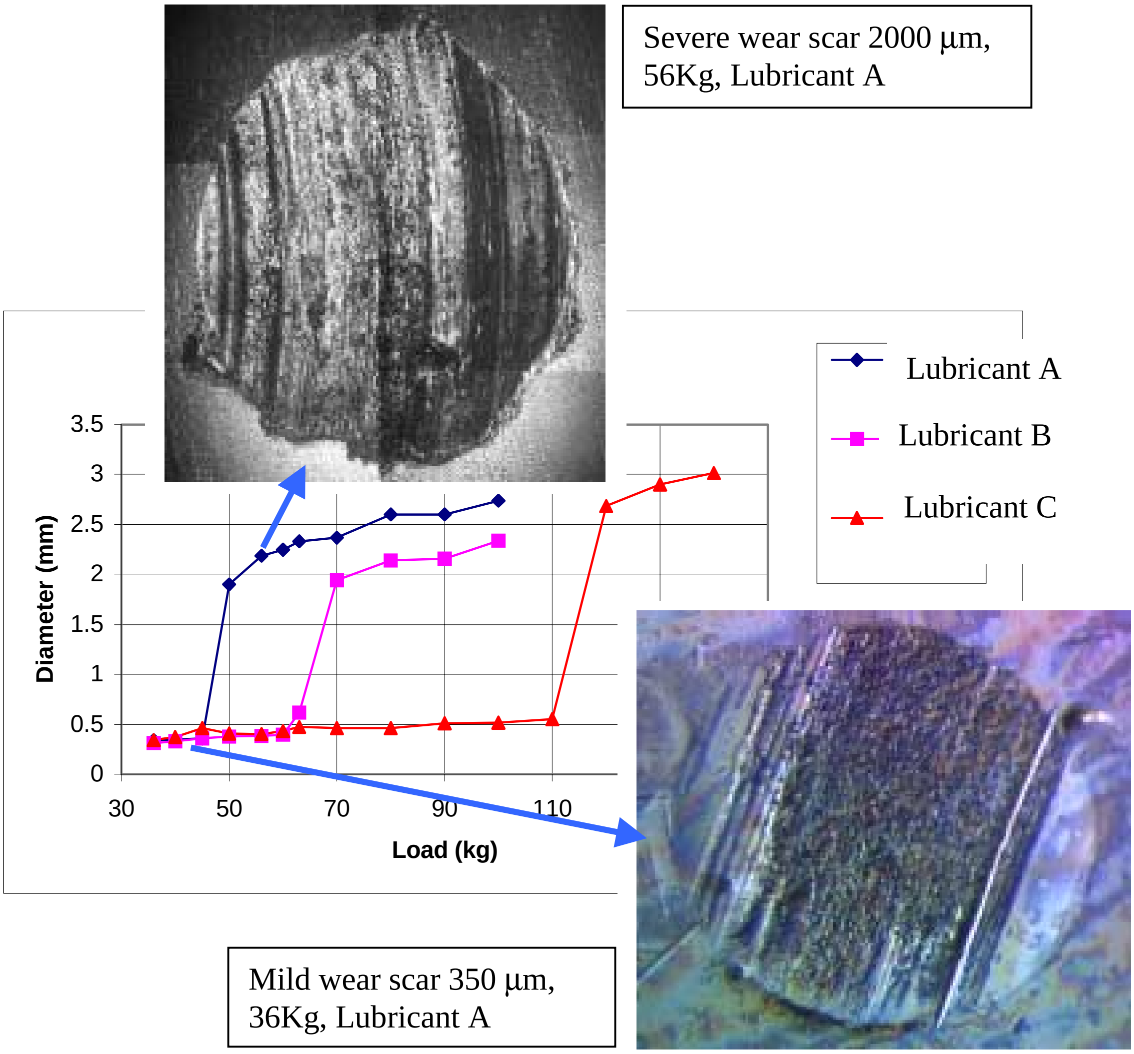


Figure 6 Behaviour in sliding wear mode – four ball machine

6. Sample Results

Sliding Wear

The representative results obtained for the four-ball sliding tests shown in Figure 6 depicts the wear behaviour in terms of the wear scar diameter measurements as a function of load for three lubricants. The transition from mild to severe wear is accompanied by transformations in the wear particle characteristics.
Friction behaviour is represented in Figure 7 for the mineral-based lubricant – A, before, and after the transition from mild to severe wear. The lubrication regime also undergoes transition from mixed to boundary lubrication with a corresponding transformation in the wear debris characteristics from low concentration (quantity), relatively small, (<100 µm chord length) ferrous free metal rubbing wear particles, to higher concentration and size, severe wear debris.

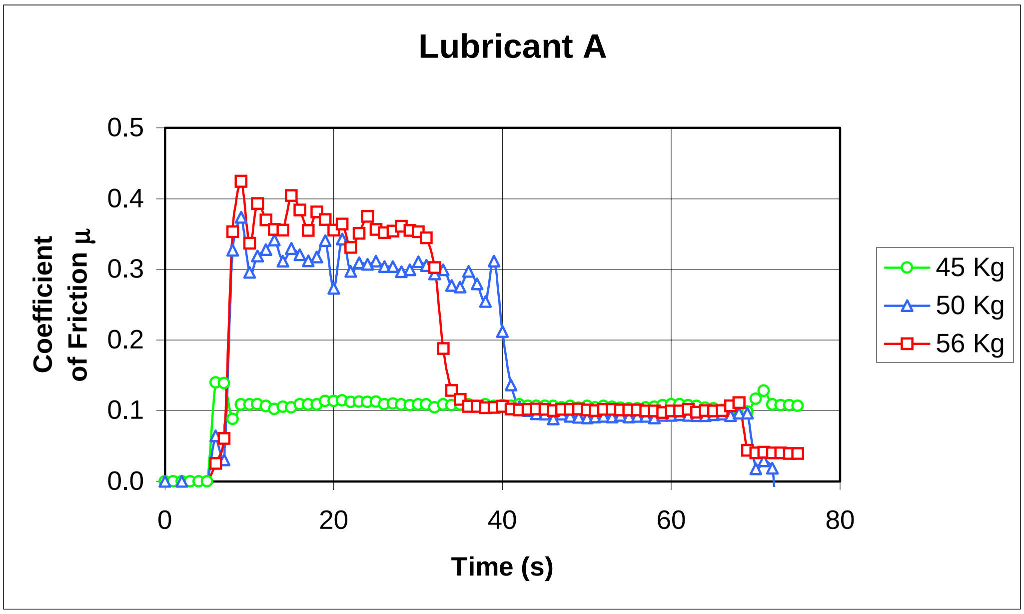


Figure 7 – Friction characteristics – Lubricant A

Preliminary indication of the way in which the acoustic emission sensor behaves is demonstrated in Figure 8. This shows that the increase in the number of hits recorded coincides with the increase in friction. The snapshot of the results presented here suggests that the AE sensor is more immediately responsive than the measurement of the friction behaviour to the rapid transitions occurring at the contact as the transition takes place from mild to severe wear.

Similar wear debris characteristics are obtained from the pin-on-disc and gear tests in which the influence of load, speed, oil temperature and contact geometry are assessed in relation to solid material and lubricant properties.

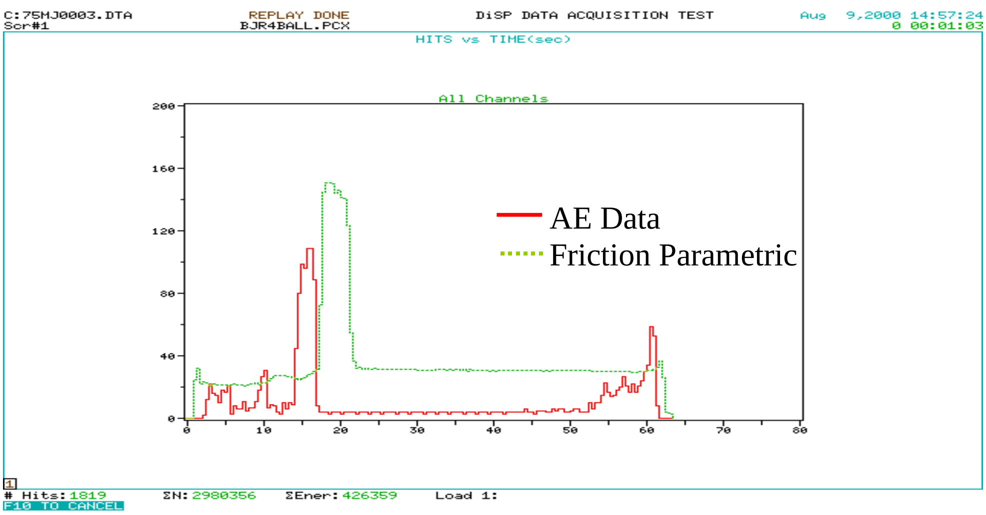
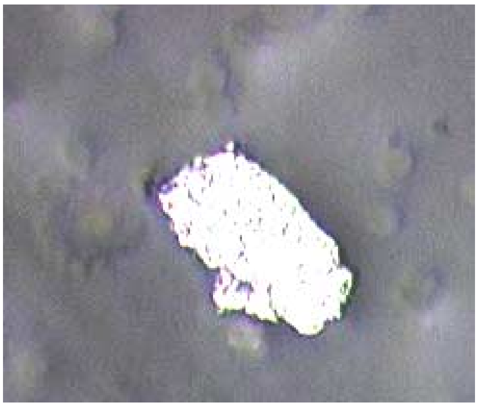


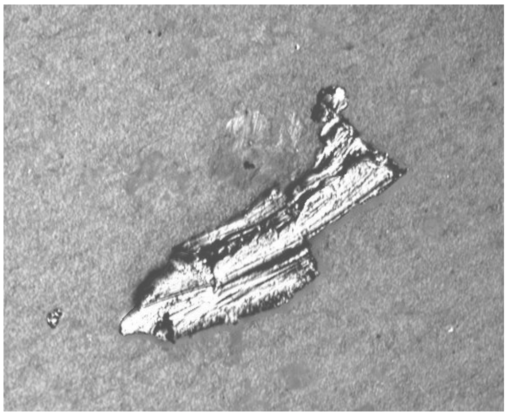
Figure 8 Comparison between AE monitoring and friction trace – Four ball sliding test

Pitting Fatigue

Debris captured form the rolling four ball and bearing fatigue test machines confirm that particle shape and surface features are quite distinct from sliding wear – compare Figures 9 and 10. The fact that the shape characteristics are distinguishable is important in relation to the use of on-line optical monitoring systems in which it is not possible to identify surface features.



Mild Wear – chord length 30μm



Severe Wear – chord length 230μm

Figure 9 Mild and severe sliding wear particles – four ball machine (sliding contact).

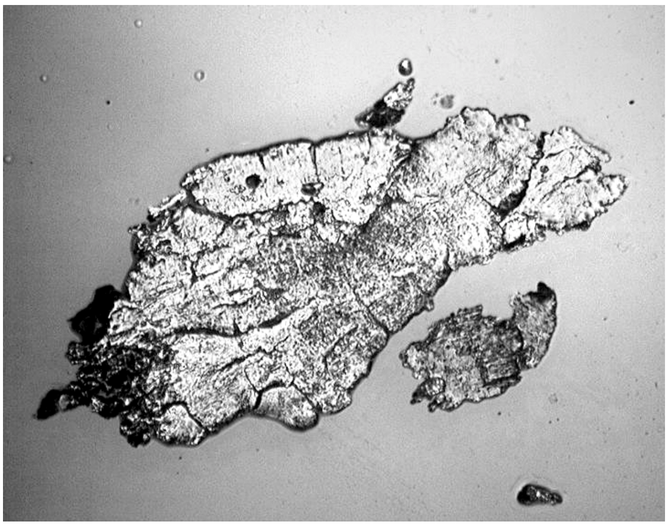


Figure 10 – Pitting fatigue wear particle – four ball machine (rolling contact) – chord length 450μm.

7. Processing data

The process of developing numerical procedures for arbitrarily distinguishing one type of wear particle from another demands that a probability-based approach be adopted, such as Neural or Bayesian belief net methods, (1,5). To satisfy training and validity test requirements requires that a sufficient number of 'known' particles in each category be identified – ideally, of the order of one hundred for each type. This has led to the setting up of a generic form of wear particle atlas (data-base) from which the population required for training and testing is drawn. (18).

This approach forms the basis for the methods and procedures being developed and applied at NRL for wear type identification in connection with the LASER NET FINES system for monitoring wear debris.

As more data becomes available from the current and on-going series of tests, the knowledge database will continue to be extended by coupling the wear characteristics debris to the additional data obtained from acoustic emission and vibration sensor measurements and analysis.

8. Closure

Numerous controlled friction and wear tests have been conducted to replicate several different forms of wear behaviour commonly encountered in operational machinery. The data thus obtained has been archived and correlated in the first instance with the results of wear debris analysis. The present and on-going implementation of a detailed test programme will ultimately culminate in the fusion of data derived from the results of wear debris, acoustic emission and vibration analysis data. It is intended by this means to establish how such techniques can best be utilised in first detecting and tracking the deterioration of critical components from the early wear regime to the point where maintenance action is required. The mathematical - statistical modelling of the data by researchers at the Naval Research Laboratory is expected to lead eventually to the development of improved methods for undertaking the task of detecting and diagnosing ship-board and airborne facilities which will be based primarily on the co-ordinated utilisation of on-line sensor technology.

Acknowledgements

The authors wish to record with grateful thanks the financial support provided by the Office of Naval Research under the auspices of the NICOP II program which has enabled this investigation to be carried out.

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